

# Measuring the Navigation Multipath Channel – A Statistical Analysis

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## BIOGRAPHY

Alexander Steingass was born in Mettmann, Germany in 1969. He received his Dipl. Ing. diploma in Electrical Engineering in 1997 (University of Ulm, Germany). Since then he has been a research scientist at the German Aerospace Centre DLR – Institute of Communications and Navigation. He has been involved in several projects in the area of satellite navigation and location dependent mobile services. In 2002 he was promoted Dr. Ing. at the University of Essen.

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## ABSTRACT

In this paper we present first statistical results of a high resolution measurement campaign, investigating the environment of satellite navigation receivers for land mobile applications, where reflections from buildings etc. decrease the accuracy of the positioning.

## INTRODUCTION

An important point in the choice of the signal format for the Galileo System is the multipath transmission channel. Studies concerning the signal structure (e.g. ESA Signal Design Study [1]) have clearly shown that the synchronisation performance of a specific signal strongly depends on reflections from the environment. In particular short delayed reflections significantly decrease the performance of the receiver. The positioning error even aggravates if these

reflections are strong and slowly varying over time, which is the predominant effect in pedestrian applications. Although narrow-band channels like GSM (COST 207 [2]) or UMTS channels have been measured in the past, it became necessary to analyse the wide-band navigation channel in order to minimize multipath effects in the high accuracy receivers of the future. For these reasons we measured the channel from a simulated satellite to a receiver in critical urban, suburban and rural scenarios. This paper presents the first statistical results and conclusions for land mobile applications.

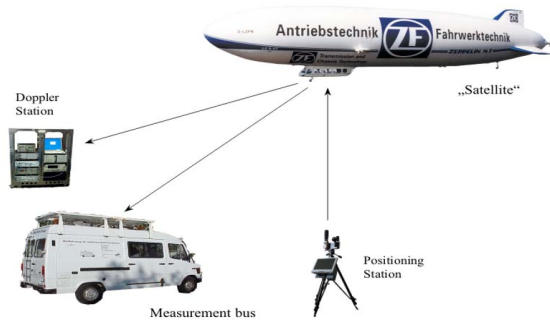
For more information on the campaign and measurement results please refer to earlier publications [3-6].

## CHANNEL MEASUREMENT

The satellite was simulated by a Zeppelin NT operating at distances from 1500 m up to 4000 m from the receiver. We transmitted a special measurement signal with 10W and a bandwidth of 100 MHz. The transmitted signal had a rectangular shaped line spectrum consisting of several hundred single carriers. This guaranteed a time resolution of 10 ns for the channel impulse response. After applying a FFT onto the received signal the system behaved as if we had sent an impulse into the channel [7]. A very high resolution is necessary for the planned wide-band services of Galileo using BOC (Binary Offset Coding) signal structures. By applying an ESPRIT (Estimation of Signal Parameters via Rotational Invariance Techniques)-based super resolution algorithm, the time resolution for the final model will be increased to 1 ns. To achieve this high time resolution we used specially assembled rubidium clocks with an Allan variance of  $10^{-11}$  s over an integration time of 1 s as references for the measurement devices.

For accurate positioning the Zeppelin was filmed by a camera station situated on the ground directly beyond the airship (see **Figure 1**). The image taken by this camera was transmitted via a wireless radio link to a monitor at the airship, enabling the captain to hold its

position. During the measurement the position of the Zeppelin was kept within a radius of about 20 m, which was sufficient in terms of the operational requirements.



**Figure 1:** Measurement setup

In addition, the Zeppelin transmitted a 18.8 GHz carrier whose Doppler shift was logged by a ground station in order to measure the airship's movement which is comparable to the movement of a pedestrian. These data are necessary to calculate the Doppler spreads caused by the receiver and its environment. For the measurements, a team member simulating the average pedestrian carried the receiver antenna in his hand while walking along the sidewalk. He was accompanied by a special measurement bus equipped with the channel sounder receiver, wheel sensors, laser gyros, audio and video system, data recording and GPS sensors. During the campaign 60 scenarios each lasting from 10 to 20 minutes were measured. For the land mobile channel the focus was on:

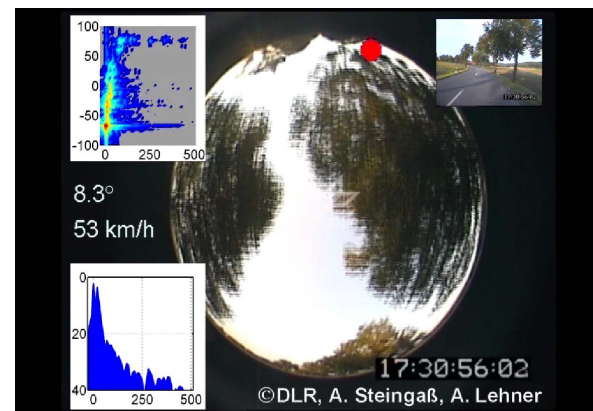
- Urban car channels (Large city – Munich including a drive along a motorway)
- Urban pedestrian channels (Large city – Munich including a shopping street)
- Suburban car and pedestrian channels (Small town – Fürstenfeldbruck)
- Rural car channels (Motorway and country roads)

An antenna showing the characteristics of a navigation system receiver antenna was used throughout the measurements to guarantee a realistic modelling.

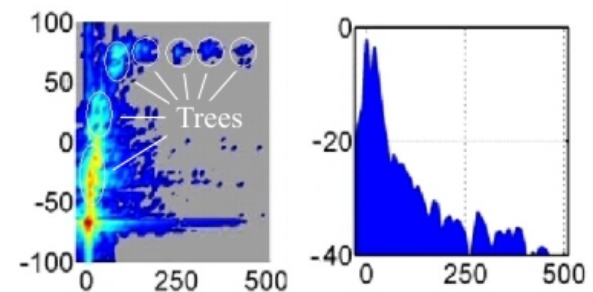
### RURAL CHANNEL – COUNTRY ROAD

For the rural scenario we chose typical motorways and country roads passing fields, meadows, forests and small villages. The multipath channel can be described by the excess delay of the reflections relative to the direct signal, their power and their phases. Surprisingly we discovered in the analysis process of the measurement data that a very critical

multipath situation exists when driving through a tree-lined alley. This situation is shown in **Figure 2** and **Figure 4**. These Figures are screenshots from videos generated for all the measurements and channel types, allowing a much better understanding of what really happens in the channel. The round image in the center is the view of a fisheye camera which was mounted on a platform on the measurement van just beside the receive antenna, thus showing which obstacles a navigation receiver “sees” in its environment. In addition there is the view of a front camera in the upper right corner. On the left side the according measurement data is plotted. The current channel impulse response at the bottom for a relative delay range from 0 to 500 ns and a power of 0 to -40 dB and the Doppler delay spectrum on top with the same delay range and a Doppler range from -100 to 100 Hz. In addition the 2 numbers between these graphs show the present elevation of the incoming direct path and the ground speed of the receiver vehicle. For better illustration the red dot in the center image indicates the azimuth direction of the zeppelin to be able to pick up the geometric configuration at this moment.



**Figure 2:** Rural car channel, low elevation

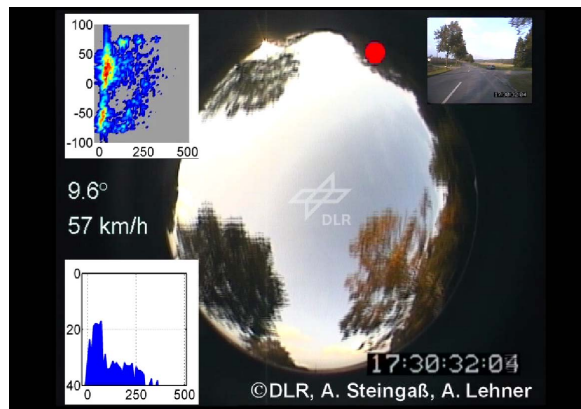


**Figure 3:** Doppler delay spectrum and impulse response (Detail of **Figure 2**)

It can be clearly seen that in **Figure 4** the Zeppelin is hidden by a tree, therefore the direct path is strongly

attenuated in comparison to the line of sight situation in **Figure 2**. On one hand it is noticeable that the attenuation of the trees is usually more than 25 dB, on the other hand reflections from the trees can be at powers up to -3 dB as can be seen in the impulse response plot of **Figure 3** (detail of **Figure 2**) where there is a strong second path after the direct pulse at about 30 ns delay. These strong reflections are best seen in the Doppler delay spectrum (white ellipses).

In this specific situation the “satellite” is in our back and we are moving away with 57 km/h. So the direct path has a negative Doppler of about -70 Hz. The trees in front act as reflectors and appear in the Doppler delay spectrum with the according positive Doppler and a large delay. As we approach the trees, each reflection moves through the plot from the upper right corner on a bow down passing close to the direct signal, first gaining power and decreasing the delay and in a second phase decreasing the Doppler as the van passes by the tree before the reflection vanishes.



**Figure 4:** Rural car channel, low elevation

## URBAN CHANNEL – LARGE CITY

During the measurements the whole range of elevations of the “satellite” from 5° to 90° was covered. For the urban car channel two very typical scenarios are illustrated in **Figure 5** and **Figure 6**. A wide through street with tree-lined sidewalks and mid high buildings, and a very narrow street canyon with low visibility typical for a city centre. **Figure 7** shows the track for the car channel measurements in the centre of Munich. Starting on the Lindwurmstrasse, which is one of the main roads of the capital of the German Federal state of Bavaria, the track led us through narrower roads, street canyons and large city squares.

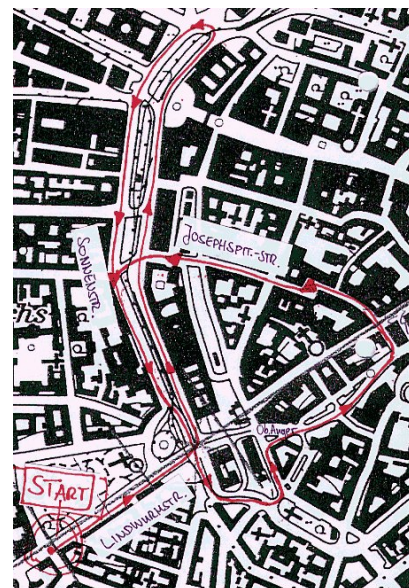
Similar to the analysis of the rural channel some typical situations can be identified using screenshots of the video images. In **Figure 8** we see the van moving along a wider through street in the city center,



**Figure 5:** Urban car channel, Munich wide street



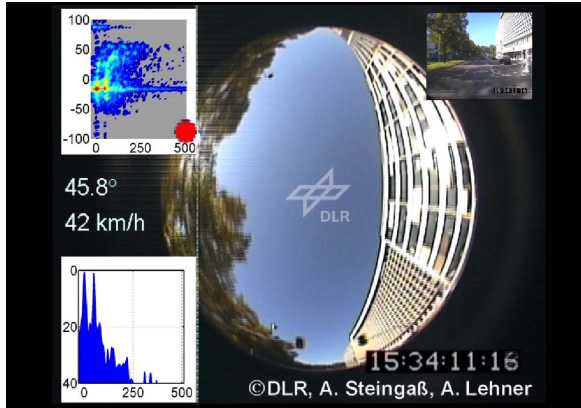
**Figure 6:** Urban car channel, Munich street canyon



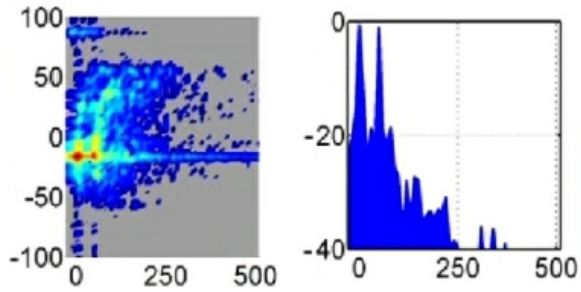
**Figure 7:** Measurement area “Lindwurmstrasse” in Munich



there is a line of trees in the middle of the street to our left and a close and continuous front row to our right. The “satellite” is on our left side at an elevation of about  $45^\circ$ . In this critical situation the impulse response plot (see **Figure 9**) shows that the reflection from the house front can be up to 0 dB as strong as the direct path and therefore causing a very large ranging error. Because the reflection zone is moving along the house as we move along the street, the delay stays constant and the Doppler shift is the same as the one of the direct path (see the Doppler delay spectrum of **Figure 9**), this is one of the worst multipath situations.

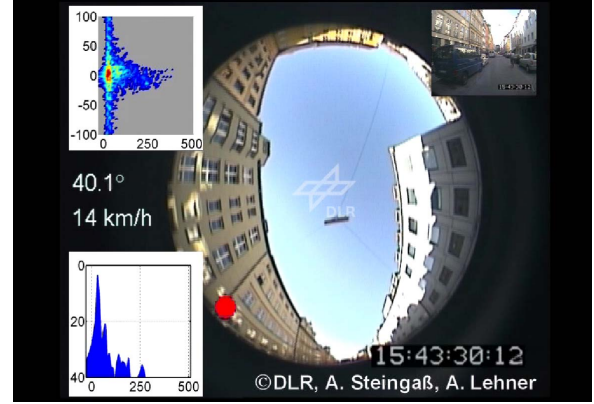


**Figure 8:** Urban car channel, Munich  $40^\circ$  elevation

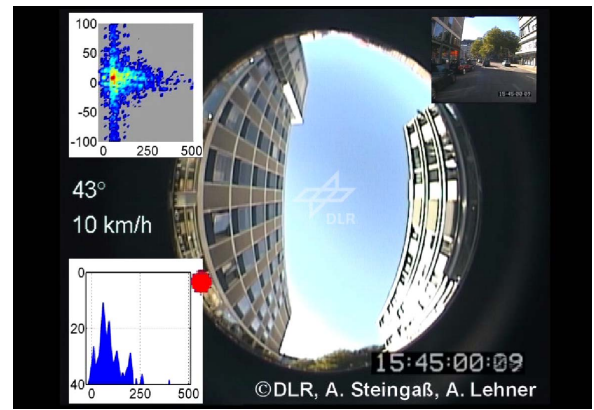


**Figure 9:** Doppler delay spectrum and impulse response (Detail of **Figure 8**)

Another scenario where large multipath errors have to be feared is the constellation in **Figure 10** and **Figure 11**. This is a narrow canyon situation where the direct path is blocked completely, the direction of the incoming signal is again almost to our side and we receive strong reflections from the houses to our right, a situation typical at powers between -5 and -20 dB. In that case a receiver is able to track the satellite only by this strong reflection which directly causes an range error according to the excess delay of the reflection.



**Figure 10:** Urban car channel, Munich  $40^\circ$  elevation



**Figure 11:** Urban car channel, Munich  $40^\circ$  elevation

## STATISTICAL ANALYSIS

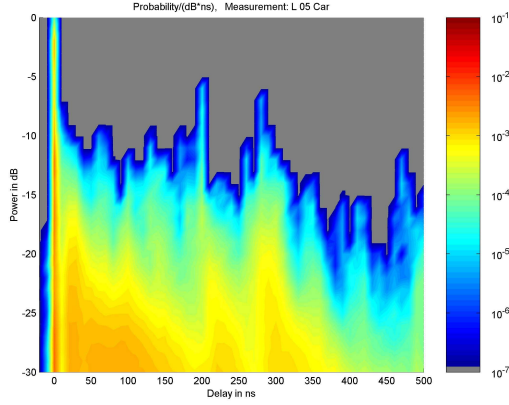
To be able to gain meaningful statistical information from the large amount of measurement data, we performed several steps of post processing. The super resolution algorithm ensures a very high time resolution and reduces the data amount enormously, which was necessary to perform a novel echo detection allowing us to determine all important measures for each reflection separately. So we were able to extract power, phase and bandwidth as well as the start and stop times, but also the change in delay and Doppler.

Since we performed a time triggered measurement on sampling impulse responses every 3 ms, a stop in front of a traffic light would give a randomly chosen impulse response a very high weight in the statistics, because this nearly constant impulse response is measured over and over again. According to this example the evaluation of a drive on low speed would suffer from these repeated impulse responses in comparison to a measurement sequence on high speed. To correct the weight of the channel impulse responses to a more way oriented measurement we

weighted the occurrence probability of the channel impulse responses by the actual speed:

$$\tilde{p}(h(\tau)) = p\left(\frac{h_k(\tau) \cdot v_k}{\sum_k v_k}\right),$$

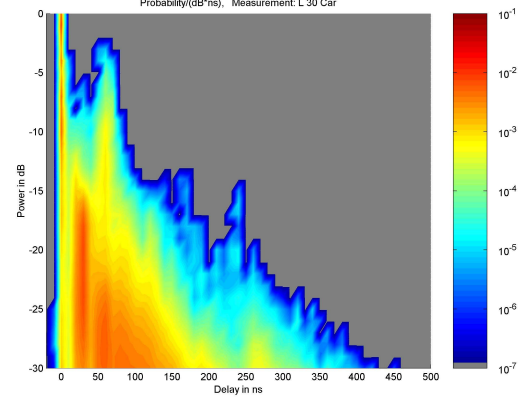
where  $h_k(\tau)$  is the  $k^{\text{th}}$  measured impulse response and  $v_k$  the present receiver speed for that snapshot.



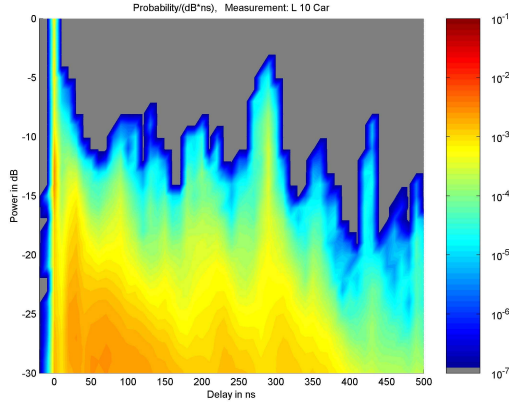
**Figure 12:** Urban car channel, Munich 5° elevation

In **Figure 12** to **Figure 19** we see the occurrence probabilities for elevations from 5° to 80° for the urban channel. Plotted is the probability density function that an echo exists at a defined power level and a defined delay relative to the direct path.

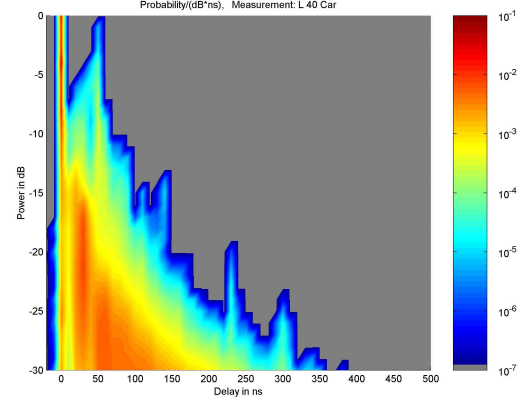
In [8,9] an “exponential” power distribution is discussed. This exponential distribution results from the assumption that the power of the reflectors is the same for all reflectors and the received power is



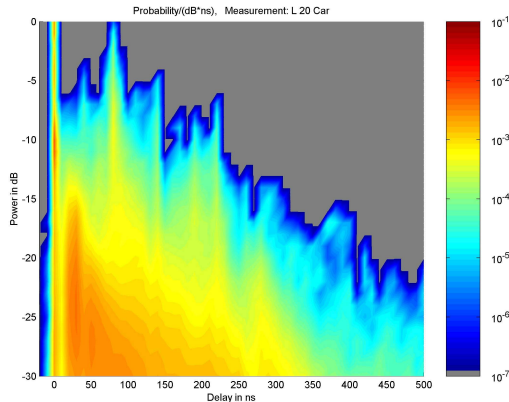
**Figure 15:** Urban car channel, Munich 30° elevation



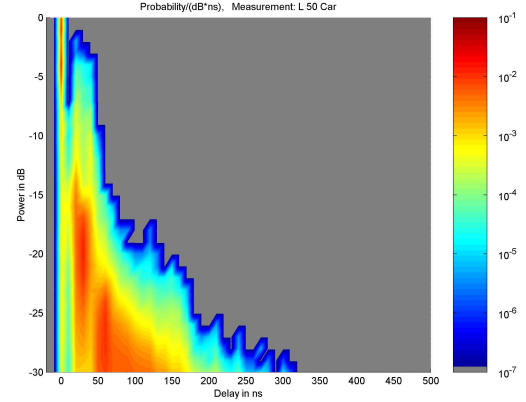
**Figure 13:** Urban car channel, Munich 10° elevation



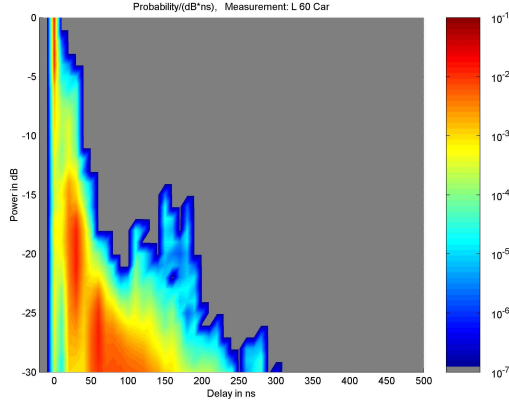
**Figure 16:** Urban car channel, Munich 40° elevation



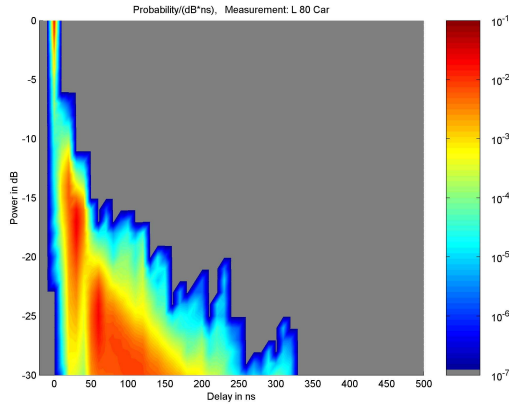
**Figure 14:** Urban car channel, Munich 20° elevation



**Figure 17:** Urban car channel, Munich 50° elevation

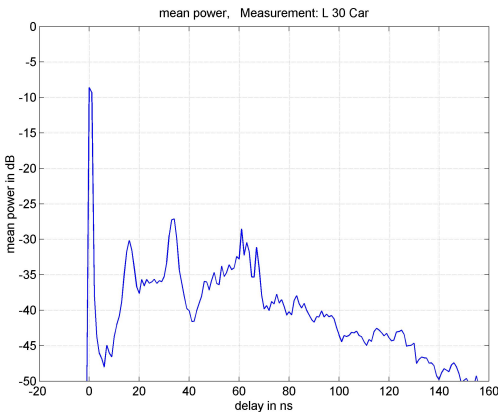


**Figure 18:** Urban car channel, Munich 60° elevation



**Figure 19:** Urban car channel, Munich 80° elevation

decreasing by  $1/D^2$ , where  $D$  is the distance between receiver and reflector. In our measurement results we can confirm the existence of an primarily exponential shape but the slope of the function is extremely dependent on the elevation. Where at 5° elevation the channel length is larger than 1us, the channel length at 80° elevation is around 300ns (see **Figure 19**). This surprisingly short multipath channel makes clear why



**Figure 20:** Mean expected power, urban 30° elevation

multipath mitigation is so problematic in urban areas. As it can clearly be seen in **Figure 12** there are discrepancies from the exponential shape. In this Figure there are accumulations of echoes at 200 and 300 ns. These clusters are significantly represented at all power levels. They are originated from distinct street widths, distinct house heights and minimum distances car and front rows. These clusters are a typical characteristic of the urban channel. In dependency of the elevation both the likelihood and the delay of these clusters vary. As a general tendency it can be said that with an increasing elevation their delay shortens and their power increases.

Another important characteristic of the urban channel is a gap in the close environment of the receiver up to delays of about 15 ns. This can be best seen in **Figure 20**. In this example (30° elevation in the urban scenario) we plotted the mean expected power of the channel impulse response:

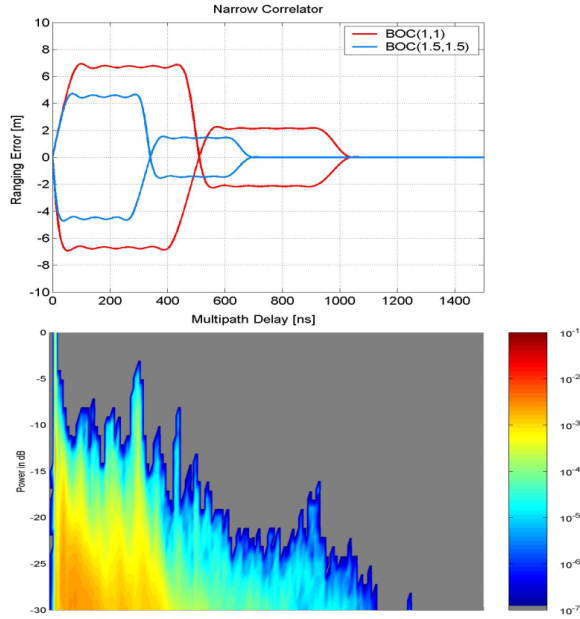
$$\bar{P}(\tau) = \int P_i \cdot p(P_i, \tau) dP_i$$

where  $p(P_i, \tau)$  is the likelihood of a reflection with power  $P_i$  and delay  $\tau$ .

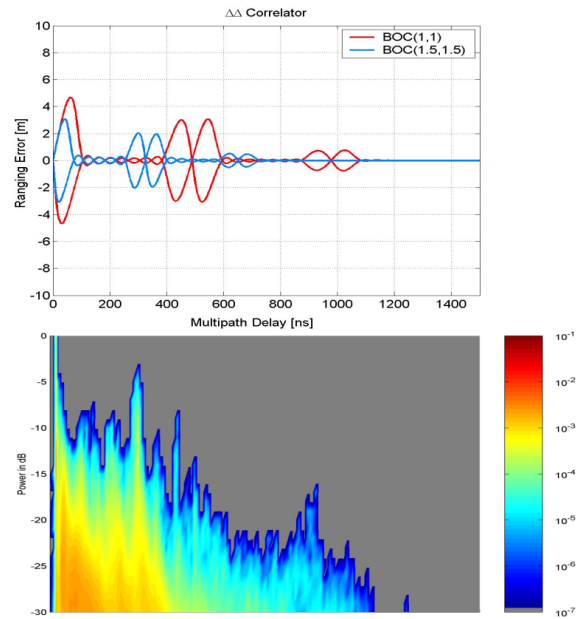
Our explanation of this gap is that a car keeps always clear of obstacles such as house fronts. A typical distance seems to be 5m between the car and the reflection point.

## IMPACTS ON GALILEOS SYSTEM DESIGN

The knowledge we gained from this unique high resolution multipath channel analysis can now be used to compare the performance of receiver architectures or several system parameters e.g. different signal structures. There have been long discussions concerning the candidates for Galileo's L1 signal. **Figure 21** and **Figure 22** show the comparison of the multipath performance for a BOC(1,1) and a BOC(1.5,1.5) signal. The upper part is a plot of the error envelope [10], which gives us the maximum error in range measurement, if there is a single reflection at a certain delay. The lower part in both Figures is the presented statistic for an urban multipath scenario at a low elevation of 10°. Using a narrow correlator (**Figure 21**) the error envelope shows two sensitive delay regions. By increasing the signal bandwidth the error envelope becomes smaller and shorter, therefore producing less position error. Even in case of this low elevation, where we have a long channel, we see that the difference of the 2 BOC signals is not staggering, because most of the multipath error will be caused by strong reflections at about 300ns. To mask that out we would need a signal with a much larger bandwidth.



**Figure 21:** Error envelope narrow correlator [10]



**Figure 22:** Error envelope  $\Delta\Delta$  correlator [10]

Applying a  $\Delta\Delta$  correlator results in the graphs shown in **Figure 22**. The error envelope decreases much faster after the first maximum but has characteristic side maxima. Although one would expect that the BOC(1.5,1.5) performs always better, surprisingly we see in this example, that scenarios exist where the BOC(1,1) clearly outperforms the BOC(1.5,1.5), because the delay zone of strong high probable reflections at 300ns directly falls together with the side maxima of the BOC(1.5,1.5). But one should mention that this situation only occurs for elevations

below  $20^\circ$  where satellite reception is rare in urban scenarios.

## CONCLUSIONS

To evaluate the reflections in urban, suburban and rural environments a measurement campaign in Autumn 2002 was performed. The main outcome is the strong elevation dependency of the channel. The surprisingly short channel shows basically an exponential decrease but also clusters of echoes at distinct delays. Furthermore we were able to prove that it is very unlikely that echoes occur before 15ns. The gained statistics from our measurements can be used in the future as an apriori probability function in combination with Bayes rule to improve the multipath mitigation. For the navigation application it is very important that many short delayed echoes occur. This adverse characteristic of the measured channel must be taken into account in the design phase of new systems and receivers. It can explain the lack of performance in critical situations.

## OUTLOOK

We are currently working on the synthesis of the measurement data to a land mobile channel model for navigation purposes. We expect this model to be finished in 2005.

## ACKNOWLEDGEMENTS

We would like to thank all of our colleagues of the DLR who supported us during the last two years on organizing this very demanding project. During the two weeks of our measurements over 60 research scientists and staff members worked for this project and contributed to its success. In addition we would like to thank Günter Hein and José Angel Rodriguez of the University of Federal Allied Forces in Munich for supplying the error envelopes for the Galileo signal candidates.

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